CLEO-c and CESR-c: Allowing Quark Flavor Physics to Reach its Full Potential.

Ian Shipsey
Deprtment of Physics
Purdue University
West Lafayette, IN 47907, U.S.A.

Abstract

We report on the physics potential of a proposed conversion of the CESR machine and the CLEO detector to a charm and QCD factory: "CLEO-c and CESR-c" that will make crucial contributions to quark flavor physics this decade, and may offer our best hope for mastering non-perturbative QCD, which is essential if we are to understand strongly coupled sectors in the new physics that lies beyond the Standard Model.

1 Executive Summary

The goals of quark flavor physics are: to test the consistency of the Standard Model (SM) description of quark mixing and CP violation, to search for evidence of new physics, and to sort between new physics scenarios initially uncovered at the LHC. This will require a range of measurements in the quark flavor changing sector of the SM at the per cent level. These measurements will come from a variety of experiments including BABAR and Belle and their upgrades, full exploitation of the facilities at Fermilab (CDF/D0/BTeV) and at the LHC (CMS/ATLAS/LHC-b), and experiments in rare kaon decays.

However, the window to new physics that quark flavor physics can provide, has a curtain drawn across it. The curtain represents hadronic uncertainty. The study of weak interaction phenomena, and the extraction of quark mixing matrix parameters remain limited by our capacity to deal with non-perturbative strong interaction dynamics. Techniques such as lattice QCD (LQCD) directly address strongly coupled theories and have the potential to eventually determine our progress in many areas of particle physics. Recent advances in LQCD have produced a wide variety of calculations of non-perturbative quantities with accuracies in the 10-20% level for systems involving one or two heavy quark such as B and D mesons, and Ψ and Υ quarkonia. The techniques needed to reduce uncertainties to 1-2% precision exist, but the path to higher precision is hampered by the absence of accurate charm data against which to test and calibrate the new theoretical techniques.

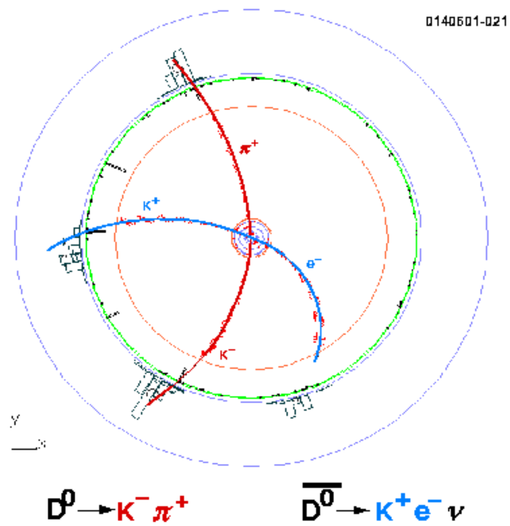

Figure 1: A doubly tagged event at the $\psi(3770)$.

To meet this challenge the CLEO collaboration has proposed to operate CLEO and CESR as a charm and QCD factory at charm threshold where the experimental conditions are optimal. In a three year focused program CLEO-c will obtain charm data samples one to two orders of magnitide larger than any previous experiment operating in this energy range, and with a detector that is significantly more powerful than any previous detector to operate at charm threshold. CLEO-c has the potential to provide a unique and crucial validation of LQCD with accuracies of 1-2%.

If LQCD is validated, CLEO-c data will lead to a dramatic improvement in our knowledge of the quark couplings in the charm sector. In addition CLEO-c validation of lattice calculations, combined with B factory, Tevatron, and LHC data will allow a significant improvement in our knowledge of quark couplings in the beauty sector. The impact CLEO-c will have on our knowledge of the CKM matrix makes the experiment an essential step in the quest to understand the origin of CP violation and quark mixing. CLEO-c allows quark flavor physics to reach its full potential, by enabling the heavy flavor community to draw back the curtain of hadronic uncertainty, and thereby see clearly through the window to the new physics that lies beyond the SM. Of equal importance, CLEO-c allows us to significantly advance our understanding and control over strongly-coupled, non-perturbatyive quantum field theories in general. An understanding of strongly coupled theories will be a crucial element in helping to interpret new phenomena at the high energy frontier.

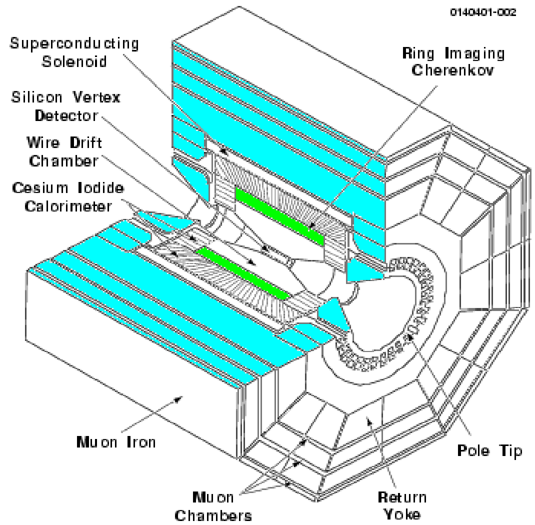

Figure 2: The CLEO III detector.

2 Introduction

For many years, the CLEO experiment at the Cornell Electron Storage Ring, CESR, operating on the Υ(4S) resonance, has provided most of the world's information about the B_d and B_u mesons. At the same time, CLEO, using the copious continuum pair production at the Υ(4S) resonance has been a leader in the study of charm and τ physics. Now that the asymmetric B factories have achieved high luminosity, CLEO is uniquely positioned to advance the knowledge of quark flavor physics by carrying out several measurements near charm threshold, at center of mass energies in the 3.5-5.0 GeV region. These measurements address crucial topics which benefit from the high luminosity and experimental constraints which exist near threshold but have not been carried out at existing charm factories because the luminosity has been too low, or have been carried out previously with meager statistics. They include:

1. Charm Decay constants f_D, f_{D_s}
2. Charm Absolute Branching Fractions
3. Semileptonic decay form factors
4. Direct determination of V_{cd} & V_{cs}
5. QCD studies including:
   Charmonium and bottomonium spectroscopy
   Glueball and exotic searches

Table 1: Summary of CLEO-c charm decay measurements.

Topic	Reaction	Energy (MeV)	L (fb^{-1})	current sensitivity	CLEO-c sensitivity
Decay constant					
f_D	$D^+ \to \mu^+\nu$	3770	3	UL	2.3%
f_{D_s}	$D_s^+ \to \mu^+\nu$	4140	3	14%	1.9%
f_{D_s}	$D_s^+ \to \mu^+\nu$	4140	3	33%	1.6%
Absolute Branching Fractions					
$Br(D^0 \to K\pi)$		3770	3	2.4%	0.6%
$Br(D^+ \to K\pi\pi)$		3770	3	7.2%	0.7%
$Br(D_s^+ \to \phi\pi)$		4140	3	25%	1.9%
$Br(\Lambda_c \to pK\pi)$		4600	1	26%	4%

Measurement of R between 3 and 5 GeV, via scans
Measurement of R between 1 and 3 GeV, via ISR

6. Search for new physics via charm mixing, CP violation and rare decays

7. τ decay physics

The CLEO detector can carry out this program with only minimal modifications. The CLEO-c project is described at length in [1] - [11]. A very modest upgrade to the storage ring is required to achieve the required luminosity. Below, we summarize the advantages of running at charm threshold, the minor modifications required to optimize the detector, examples of key analyses, a description of the proposed run plan, and a summary of the physics impact of the program.

2.1 Advantages of running at charm threshold

The B factories, running at the $\Upsilon(4S)$ will have produced 500 million charm pairs by 2005. However, there are significant advantages of running at charm threshold:

1. Charm events produced at threshold are extremely clean.

2. Double tag events, which are key to making absolute branching fraction measurements, are pristine.

3. Signal/Background is optimum at threshold.

4. Neutrino reconstruction is clean.

5. Quantum coherence aids D mixing and CP violation studies.

These advantages are dramatically illustrated in Figure 1, which shows a picture of a simulated and fully reconstructed $\psi(3770) \to D\bar{D}$ event.

2.2 The CLEO-III Detector : Performance, Modifications and issues

The CLEO III detector, shown in Figure 2, consists of a new silicon tracker, a new drift chamber, and a Ring Imaging Cherenkov Counter (RICH), together with the CLEO II/II.V magnet, electromagnetic calorimeter and muon chambers. The upgraded detector was installed and commissioned during the Fall of 1999 and Spring of 2000. Subsequently operation has been very reliable (see below for a caveat) and a very high quality data set has been obtained. To give an idea of the power of the CLEO III detector in Figure 3 (left plot) the beam constrained mass for the Cabibbo allowed decay $B \to D\pi$ and the Cabibbo suppressed decay $B \to DK$ with and without RICH information is shown.

The latter decay was extremely difficult to observe in CLEO II/II.V which did not have a RICH detector. In the right plot of Figure 3 the penguin dominated decay $B \to K\pi$ is shown. This, and other rare B decay modes are observed in CLEO III with branching ratios consistent with those found in CLEO II/II.V, and are also in agreement with recent Belle and BABAR results. Figure 3 is a demonstration that CLEO III performs very well indeed.

Unfortunately, there is one detector subsystem that is not performing well. The CLEO III silicon has experienced an unexpected and unexplained loss of efficiency. The silicon detector will be replaced with a wire vertex chamber for CLEO-c. We note that if one was to design a charm factory detector from scratch the tracking would be entirely gas based to ensure that the detector material was kept to a minimum. CLEO-c simulations indicate that a simple six layer stereo tracker inserted into the CLEO III drift chamber, as a silicon detector replacement, would provide a system with superior momentum resolution compared to the current CLEO III tracking system.

Due to machine issues we plan to lower the solenoid field strength to 1.0 T from 1.5 T. All other parts of the detector do not require modification. The dE/dx and Ring Imaging Cerenkov counters are expected to work well over the CLEO-c momentum range. The electromagnetic calorimeter works well and has fewer photons to deal with at 3-5 GeV than at 10 GeV. Triggers will work as before. Minor upgrades may be required of the Data Acquisition system to handle peak data transfer rates. The conclusion is that, with the addition of the replacement wire chamber, CLEO is expected to work well in the 3-5 GeV energy range at the expected rates.

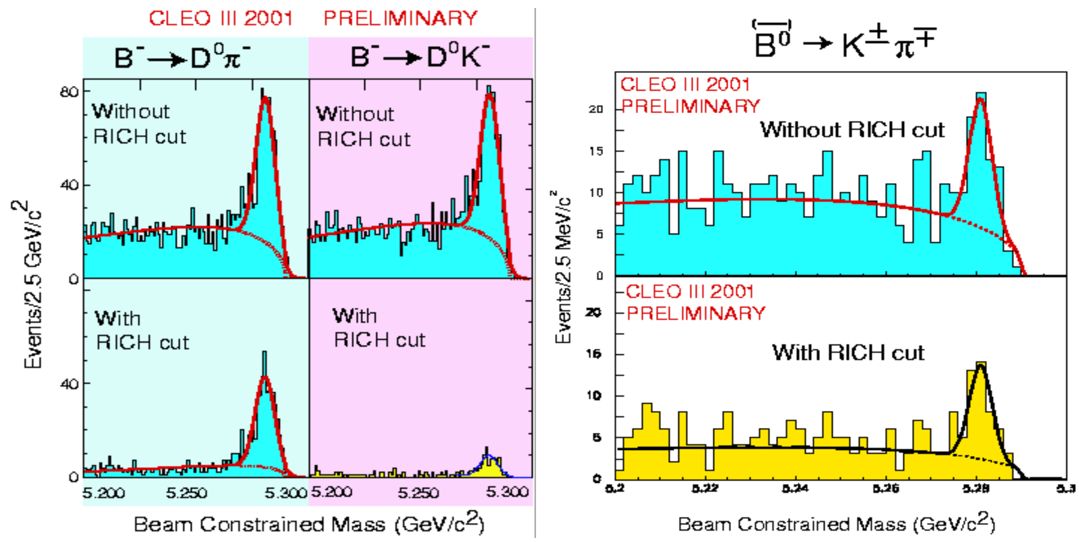

Figure 3: (Left) Beam constrained mass for the Cabibbo allowed decay $B \to D\pi$ and the Cabibbo suppressed decay $B \to DK$ with and without RICH information. The latter decay was extremely difficult to observe in CLEO II/II.V which did not have a RICH detector. (Right) The penguin dominated decay $B \to K\pi$. Both of these modes are observed in CLEO III with branching ratios consistent with those found in CLEO II/II.V.

2.3 Machine Conversion

Electron positron colliders are designed to operate optimally within a relatively narrow energy range. As the energy is reduced below design, there is a significant reduction in synchrotron radiation, which is the primary means of cooling the beam. In consequence, the luminosity drops, roughly as the beam energy to the fourth power. Without modification to the machine, CESR performance in the 3-5 GeV energy range would be modest, well below $10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. CESR conversion to CESR-c requires 18 m of wiggler magnets, to increase transverse cooling, at a cost of $\sim$ \$4M. With the wigglers installed, CESR-c is expected to achieve a luminosity in the range $2-4\times10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ where the lower (higher) luminosity corresponds to $\sqrt{s}=3.1(4.1)$GeV.

2.4 Examples of analyses with CLEO-c

The main targets for the CKM physics program at CLEO-c are absolute branching ratio measurements of hadronic, leptonic and semileptonic decays. The first of these provides an absolute scale for all charm and hence all beauty decays. The second

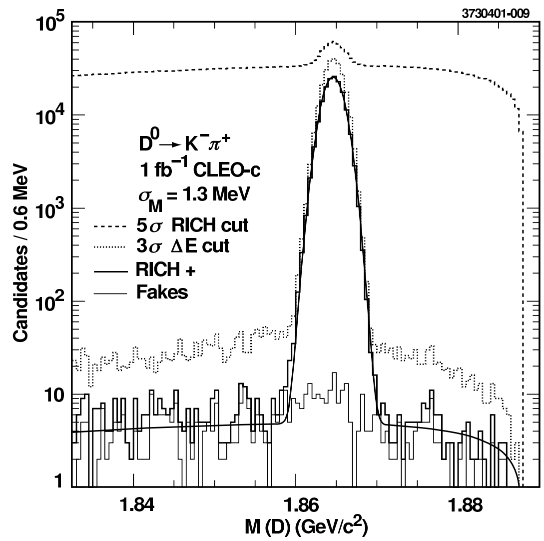

Figure 4: $K\pi$ invariant mass in $\psi(3770) \to D\bar{D}$ events showing a strikingly clean signal for $D \to K\pi$. The y axis is a logarithmic scale. The signal to background ratio is $\sim 5000/1$.

measures decay constants and the third measures form factors and, in combination with theory, allows the determination of V_{cd} and V_{cs}.

2.4.1 Absolute branching ratios

The key idea is to reconstruct a D meson in any hadronic mode. This, then, constitutes the tag. Figure 4 shows tags in the mode $D \to K\pi$. Note the y axis is a log scale. Tag modes are very clean. The signal to background ratio is $\sim 5000/1$ for the example shown. Since $\psi(3770) \to D\bar{D}$, reconstruction of a second D meson in a tagged event to a final state X, corrected by the efficiency which is very well known, and divided by the number of D tags, also very well known, is a measure of the absolute branching ratio $Br(D \to X)$. Figure 5 shows the $K^-\pi^+\pi^+$ signal from doubly tagged events. It is approximately background free. The simplicity of $\psi(3770) \to D\bar{D}$ events combined with the absence of background allows the determination of absolute branching ratios with extremely small systematic errors. This is a key advantage of running at threshold.

2.4.2 Leptonic decay $D_s \to \mu\nu$

This is a crucial measurement because it provides information which can be used to extract the weak decay constant, f_{D_s}. The constraints provided by running at threshold are critical to extracting the signal.

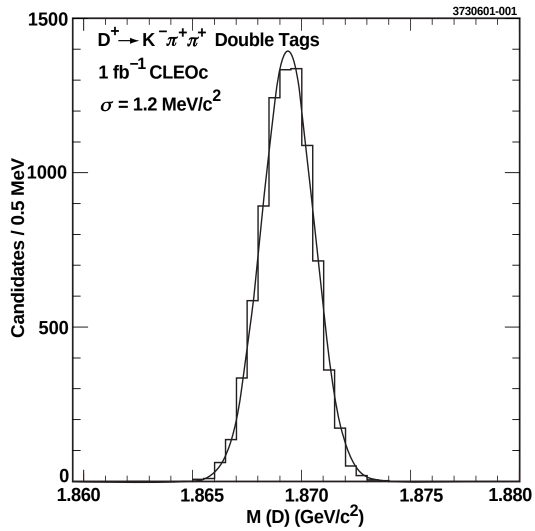

Figure 5: $K\pi\pi$ invariant mass in $\psi(3770) \to D\bar{D}$ events where the other D in the event has already been reconstructed. A clean signal for $D \to K\pi\pi$ is observed and the absolute branching ratio $Br(D \to K\pi\pi)$ is measured by counting events in the peak.

The analysis procedure is as follows:

1. Fully reconstruct one D_s, this is the tag.

2. Require one additional charged track and no additional photons.

3. Compute the missing mass squared (m_ν^2) which peaks at zero for a decay where only a neutrino is unobserved.

The missing mass resolution, which is of order $\sim m_{\pi^0}$, is sufficient to reject the backgrounds to this process as shown in Fig. 6. There is no need to identify muons, which helps reduce the systematic error. One can inspect the single prong to make sure it is not an electron. This provides a check of the background level since the leptonic decay to an electron is severely helicity-suppressed and no signal is expected in this mode.

2.4.3 Semileptonic decay $D \to \pi e^+ \nu$

The analysis procedure is as follows:

1. Fully reconstruct one D, this constitutes the tag.

2. Identify one electron and one hadronic track.

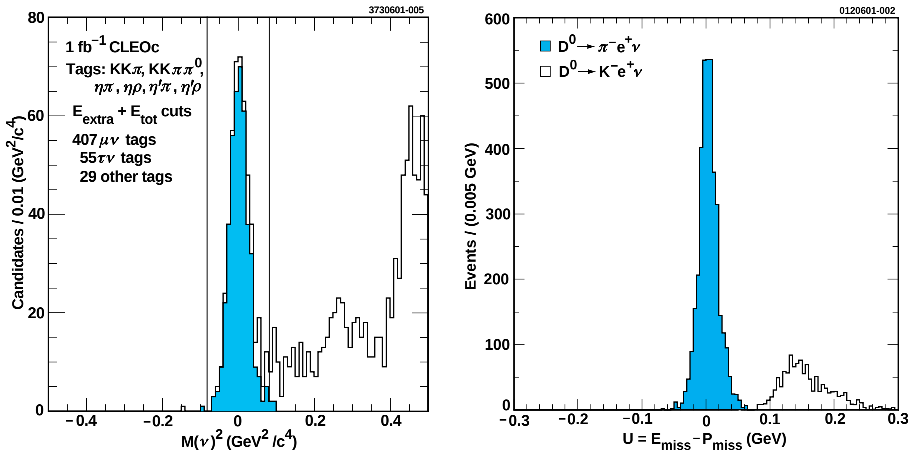

Figure 6: (Left) Missing mass squared for $D_s\bar{D}_s$ tagged pairs produced at $\sqrt{s} = 4100$ MeV. Events due to the decay $D_s \to \mu\nu$ are shaded. (Right) The difference between the missing energy and missing momentum in $\psi(3770) \to D\bar{D}$ tagged events for the Cabibbo suppressed decay $D \to \pi\ell\nu$ (shaded). The unshaded histogram arises from the ten times more copiously produced Cabibbo allowed transition $D \to K\ell\nu$ where the K is outside the fiducial volume of the RICH.

3. Calculate the variable, $U = E_{miss} - P_{miss}$, which peaks at zero when only a neutrino has escaped detection, which is the case for semileptonic decays.

Using the above procedure results in the right plot of Figure 6. With CLEO-c for the first time it will become possible to make precise branching ratio and absolute form factor measurements of every charm meson semileptonic pseudoscalar to pseudoscalar and pseudoscalar to vector transition. This will be a lattice validation data set without equal. Figure 7 shows the current precision with which the absolute semileptonic branching ratios of charm particles are known, and the precision attainable with CLEO-c.

2.5 Run Plan

CLEO-c must run at various center of mass energies to achieve its physics goals. The "run plan" currently used to calculate the physics reach is given below. This plan assumes CESR-c achieves design luminosity. Item 1 is prior to machine conversion, while the remaining items are post machine conversion.

1. 2002 : Υ's – 1-2 fb^{-1} each at $\Upsilon(1S), \Upsilon(2S), \Upsilon(3S)$
   Spectroscopy, electromagnetic transition matrix elements, the leptonic width. Γ_{ee}, and searches for the yet to be discovered h_b, η_b with 10-20 times the existing world's data sample. As of July 2002, most of this data has been collected.

Table 2: Summary of direct CKM reach with CLEO-c

Topic	Reaction	Energy (MeV)	L (fb^{-1})	current sensitivity	CLEO-c sensitivity
V_{cs}	$D^0 \to K\ell^+\nu$	3770	3	16%	1.6%
V_{cd}	$D^0 \to \pi\ell^+\nu$	3770	3	7%	1.7%

2. 2003 : $\psi(3770)$ – 3 fb^{-1}
   30 million events, 6 million tagged D decays (310 times MARK III)

3. 2004 : 4100 MeV – 3 fb^{-1}
   1.5 million D_sD_s events, 0.3 million tagged D_s decays (480 times MARK III, 130 times BES)

4. 2005 : J/ψ – 1 fb^{-1}
   1 billion J/ψ decays (170 times MARK III, 20 times BES II)

2.6 Physics Reach of CLEO-c

Tables 1, 2 , and 3, and Figures 7 and 8 summarize the CLEO-c measurements of charm weak decays, and compare the precision obtainable with CLEO-c to the expected precision at BABAR which expects to have recorded about 500 million charm pairs by 2005. While BABAR data allows improvement in the precision with which these quantities can be measured, CLEO-c clearly achieves far greater precision for many measurements. The reason for this is the ability to measure absolute branching ratios by tagging, and the absence of background at threshold. For charm quantities where CLEO-c is not dominant, it will remain comparable in sensitivity, and complementary in technique, to the B factories. Also shown in Table 3 is a summary of the data set size for CLEO-c and BES II at the J/ψ and ψ', and the precision with which R, the ratio of the e^+e^- annihilation cross section into hadrons to mu pairs, can be measured. The CLEO-c data sets are over an order of magnitude larger, the precision with which R is measured is a factor of three higher, in addition the CLEO detector is vastly superior to the BES II detector.

Taken together the CLEO-c datasets at the J/ψ and ψ' will be qualitatively and quantitatively superior to any previous dataset in the charmonium sector thereby providing discovery potential for glueballs and exotics without equal.

2.7 CLEO-c Physics Impact

CLEO-c will provide crucial validation of Lattice QCD, which will be able to calculate with accuracies of 1-2%. The CLEO-c decay constant and semileptonic data will

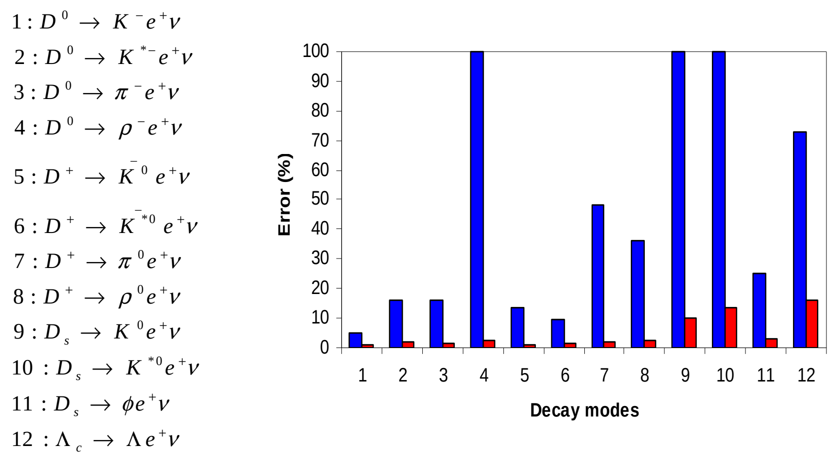

Figure 7: Absolute branching ratio current precision from the PDG (left entry) and precision attainable at CLEO-c (right entry) for twelve semileptonic charm decays.

Table 3: Comparision of CLEO-c reach to BABAR and BES

Quantity	CLEO-c	BaBar	Quantity	CLEO-c	BES-II
f_D	2.3%	10-20%	$\#J/\psi$	10^9	5×10^7
f_{D_s}	1.7%	5-10%	ψ'	10^8	3.9×10^6
$Br(D^0 \to K\pi)$	0.7%	2-3%	4.14 GeV	$1 fb^{-1}$	$23 pb^{-1}$
$Br(D^+ \to K\pi\pi)$	1.9%	3-5%	3-5 R Scan	2%	6.6%
$Br(D_s^+ \to \phi\pi)$	1.3%	5-10%			

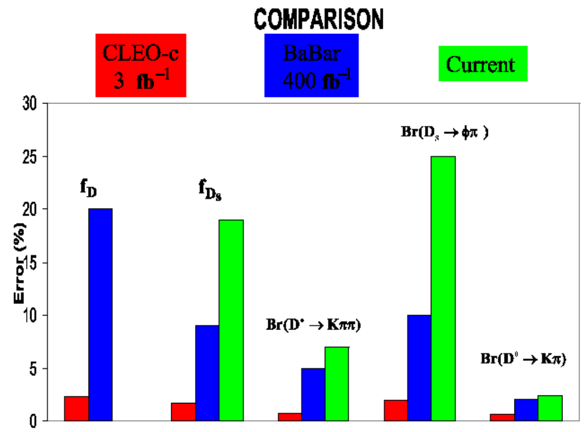

Figure 8: Comparison of CLEO-c (left) BABAR (center) and PDG2001 (right) for the charm meson decay constants and three important charm meson hadronic decay branching ratios.

provide a "golden", and timely test while CLEO-c QCD and charmonium data provide additional benchmarks. CLEO-c will provide dramatically improved knowledge of absolute charm branching fractions which are now contributing significant errors to measurements involving b's in a timely fashion. CLEO-c will significantly improve knowledge of CKM matrix elements which are now not very well known. V_{cd} and V_{cs} will be determined directly by CLEO-c data and LQCD, or other theoretical techniques. V_{cb}, V_{ub}, V_{td} and V_{ts} will be determined with enormously improved precision using B factory and Tevatron data, once the CLEO-c program of lattice validation is complete. Table 4 provides a summary of the situation. CLEO-c data alone will also allow new tests of the unitarity of the CKM matrix. The unitarity of the second row of the CKM matrix will be probed at the 3% level. CLEO-c data will also test unitarity by measuring the ratio of the long sides of the squashed cu triangle to 1.3%.

Finally the potential to observe new forms of matter; glueballs, hybrids, etc. in J/ψ decays and new physics through sensitivity to charm mixing, CP violation, and rare decays provides a discovery component to the program.

I would like to thank my CLEO colleagues for providing the opportunity to represent the collaboration at this conference. It is a privilege to be part of the CLEO collaboration. I thank Ikaros Bigi, Gustavo Burdman, Andreas Kronfeld, Peter Lepage, Zoltan Ligeti and Matthias Neubert for valuable discussions. Finally, I thank Nigel Lockyer and his support team for the superb organization of this conference.

Table 4: Current knowledge of CKM matrix elements (row one). Knowledge of CKM matrix elements after CLEO-c (row two). The improvement in the precision with which V_{cd} and V_{cs} are known is attainable with CLEO-c data combined with Lattice QCD. The improvement in precision with which V_{cb}, V_{ub}, V_{td}, and V_{ts} are known is obtained from CLEO-c validated Lattice QCD calculations and B factory and Tevatron data.

V_{cd}	V_{cs}	V_{cb}	V_{ub}	V_{td}	V_{ts}
7%	16%	5%	25%	36%	39%
1.7%	1.6%	3%	5%	5%	5%

References

[1] "CLEO-c and CESR-c : A New Frontier of Weak and Strong Interactions", CLNS 01/1742.

[2] "Report of Snowmass 2001 Working Group E2: Electron-positron Colliders for the phi to the Z", I. Shipsey on behalf of the E2 convenors, G. Burdman, J. Butler, I. Shipsey, and H. Yamamoto. Talk at the final plenary session of Snowmass, 2001. A written version of this talk is available as Z.Zhao hep-ex/0201047, to be published in *Proceedings of the 2001 DPF Snowmass Summer Study on the Future of Particle Physics.* 'All E2 working group talks (refs. 2-11) may be found at http://www.physics.purdue.edu/Snowmass2001_E2/

[3] "Another look at Charm: the CLEO-c physics program", M. Artuso, talk to the E2 Working Group.

[4] "CLEO-c and CESR-c : A New Frontier of Weak and Strong Interactions", I. Shipsey, talk to a joint E2/P2/P5 Working Group session.

[5] "Projected Non-perturbative QCD Studies with CLEO-c", S. Dytman, talk to the E4 Working Group.

[6] "CLEO-c and R measurements", L. Gibbons, talk to the E2 Working Group.

[7] "An Introduction to CLEO-c ", L. Gibbons, talk to the E2 Working Group.

[8] "CLEO-C reach in D meson Decays : Measuring absolute D meson branching fractions, D decay constants,and CKM matrix elements", D. Cassel, talk to the E2 Working Group.

[9] "Beyond the Standard Model: the clue from charm", M. Artuso, talk to the E2 Working Group.

[10] “A case for running CLEO-C at the ψ' ($\sqrt{s} = 3686$ MeV)”, S. Pordes, talk to the E2 Working Group.

[11] “Experimental Aspects of Tau Physics at CLEO-c”, Y. Maravin, talk to the E2 Working Group.